# The Shannon limit in mobile cellular systems: How far off are we?

Markus Rupp
Sebastian Caban, Christian Mehlführer
3.12.2009, Bratislava University of Technology

contact email: mrupp@nt.tuwien.ac.at
web: http://www.nt.tuwien.ac.at/rapid_prototyping

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# Outline

- MIMO Testbed
- WiMAX Measurements
  - IEEE 802.16-2004 (Section 8.3) with OFDM physical layer
  - feedback realization
  - achievable and measured throughput
- HSDPA Measurements
  - signal generation and reception
  - feedback realization
  - achievable and measured throughput
- Comparisons HSDPA vs. WiMAX
- Conclusion

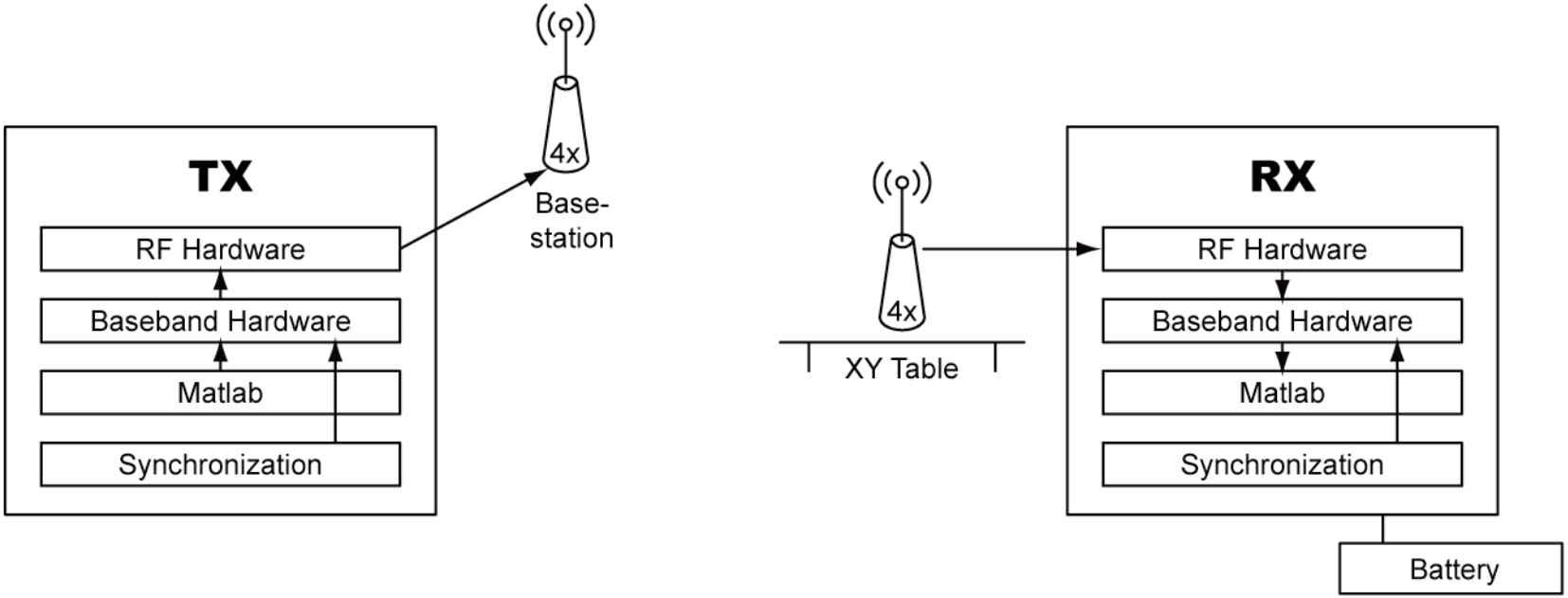
# Evaluating MIMO radio communication

- theoretically
- by pure simulation
- by channel sounding
- utilizing a testbed
- utilizing a prototype
- using the final product

degree of realism

effort

# MIMO Testbed [T1,T2]

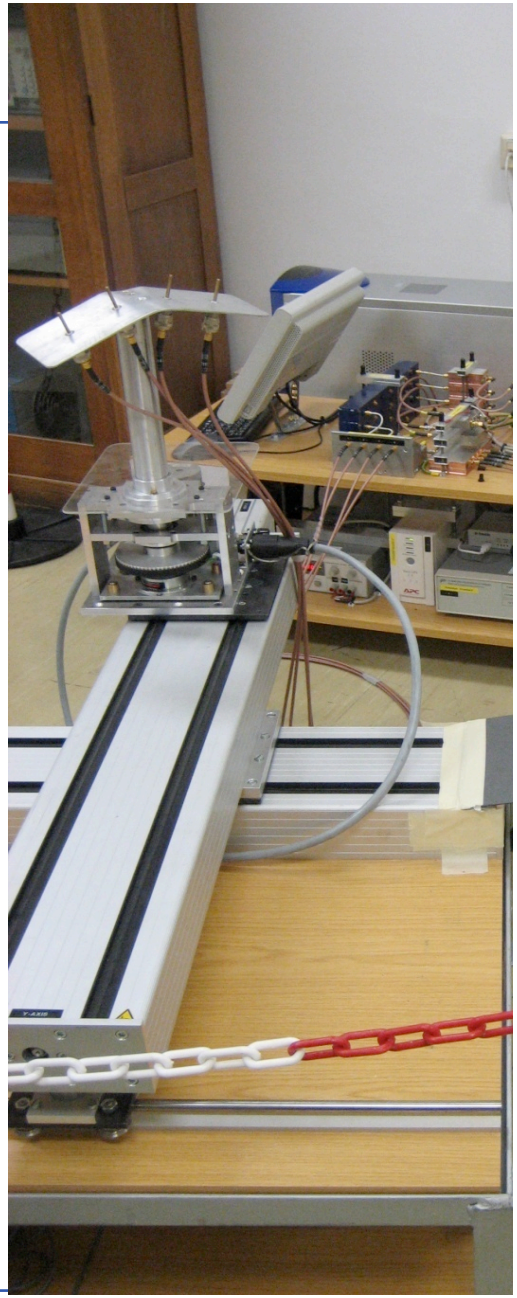



**Data is created and evaluated in Matlab ...**

| | |
|---|---|
| **Number of Antennas:** | **4x4** |
| **Bandwidth:** | **5 MHz** |
| **Center Frequency:** | **2.5 GHz** |

# MIMO Testbed [T1,T2]

- **MIMO WiMAX 802.16-2004**
  OFDM physical layer
  - including channel coding and decoding
  - SISO and MIMO
- **MIMO HSDPA (TxAA, DTxAA)**
  CDMA physical layer
  - including channel coding and decoding
  - SISO and MIMO
- **MIMO LTE (new)**



# Experimental MIMO Testbed: THE MOVIE

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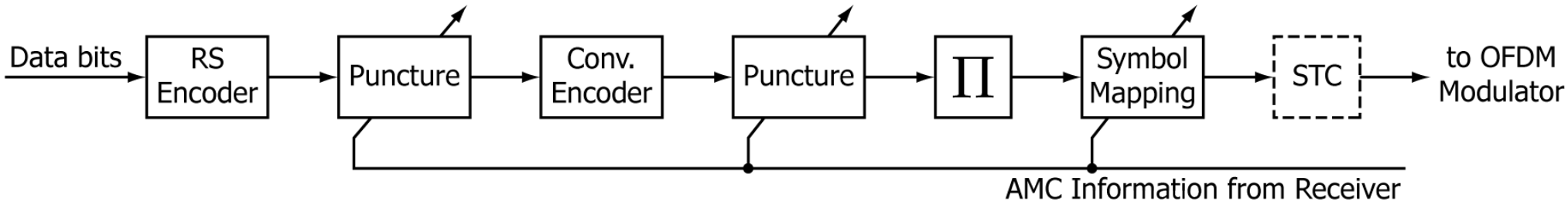
# Adaptive Modulation and Coding (AMC)

- Encoding
  - concatenated Reed-Solomon / convolutional code
  - puncturing depending on AMC information
  - optional block/convolutional turbo coding
  - Alternatively: LDPC coding
- Adaptive symbol mapping
- Optional Alamouti space-time coding

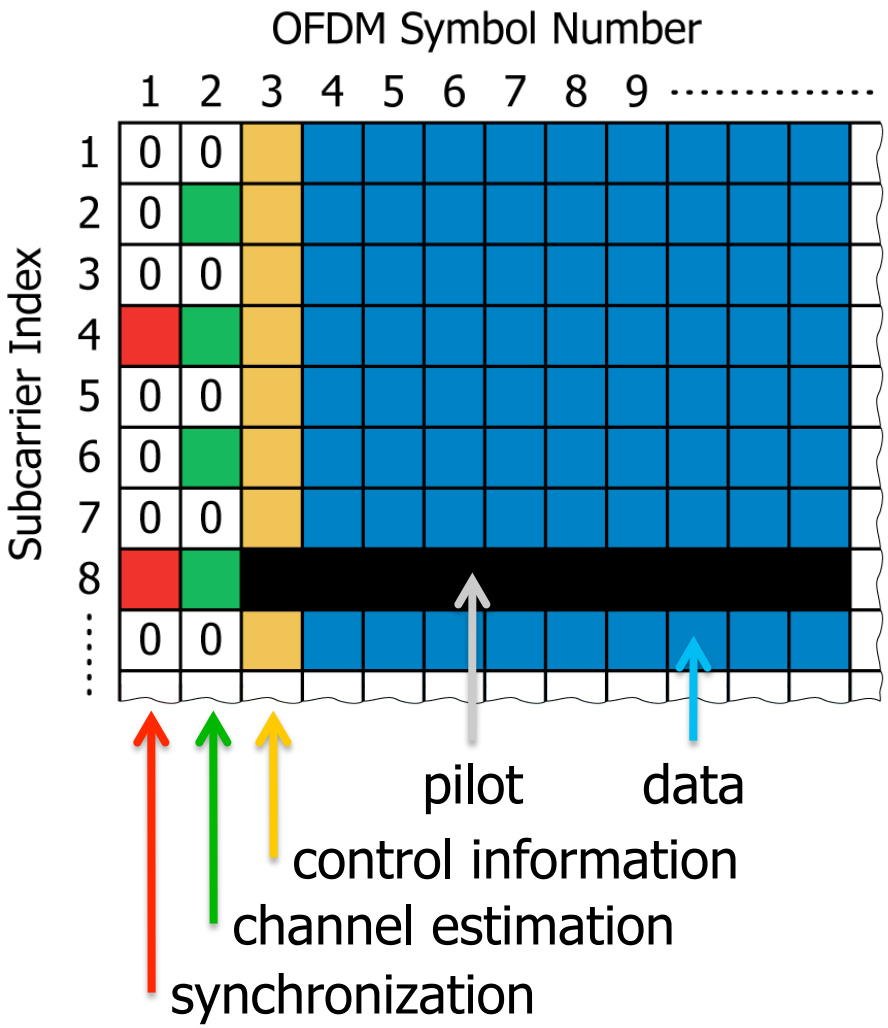


# Coding and Modulation

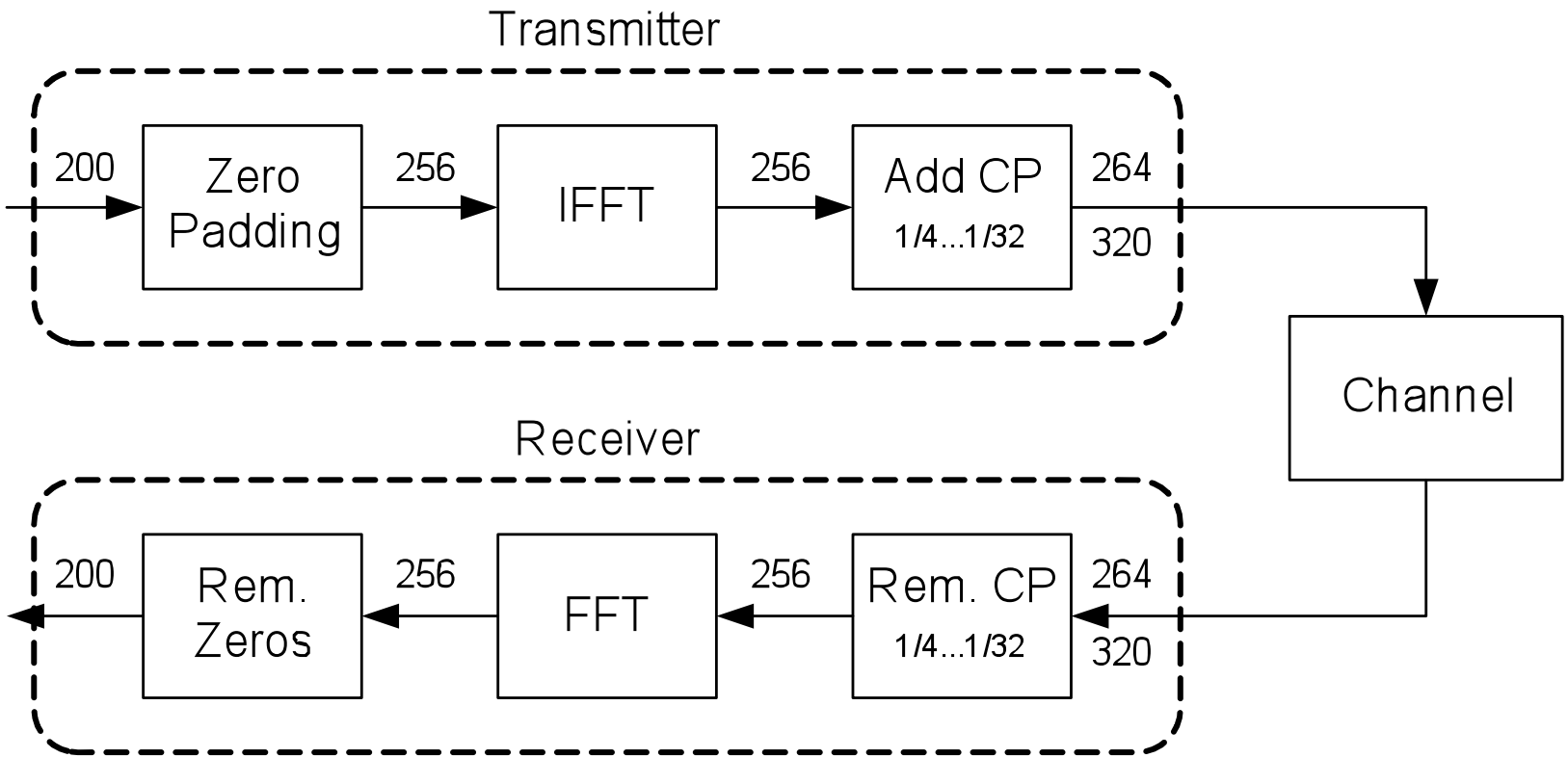
| AMC value | Modulation | RS Code Rate | CC Rate | Overall Code Rate |
|---|---|---|---|---|
| 1 | 2-PAM | 1 | 1/2 | 1/2 |
| 2 | 4-QAM | 3/4 | 2/3 | 1/2 |
| 3 | 4-QAM | 9/10 | 5/6 | 3/4 |
| 4 | 16-QAM | 3/4 | 2/3 | 1/2 |
| 5 | 16-QAM | 9/10 | 5/6 | 3/4 |
| 6 | 64-QAM | 8/9 | 3/4 | 2/3 |
| 7 | 64-QAM | 9/10 | 5/6 | 3/4 |

# OFDM Frame Structure

- 3 OFDM symbols preamble
  1. Synchronization
  2. Channel estimation
  3. Control information
- Subcarrier distribution
  - 192 data subcarriers
  - 8 pilot subcarriers
  - 1 zero DC subcarrier
  - 55 guard band subcarriers
  - $\rightarrow$ 256 total



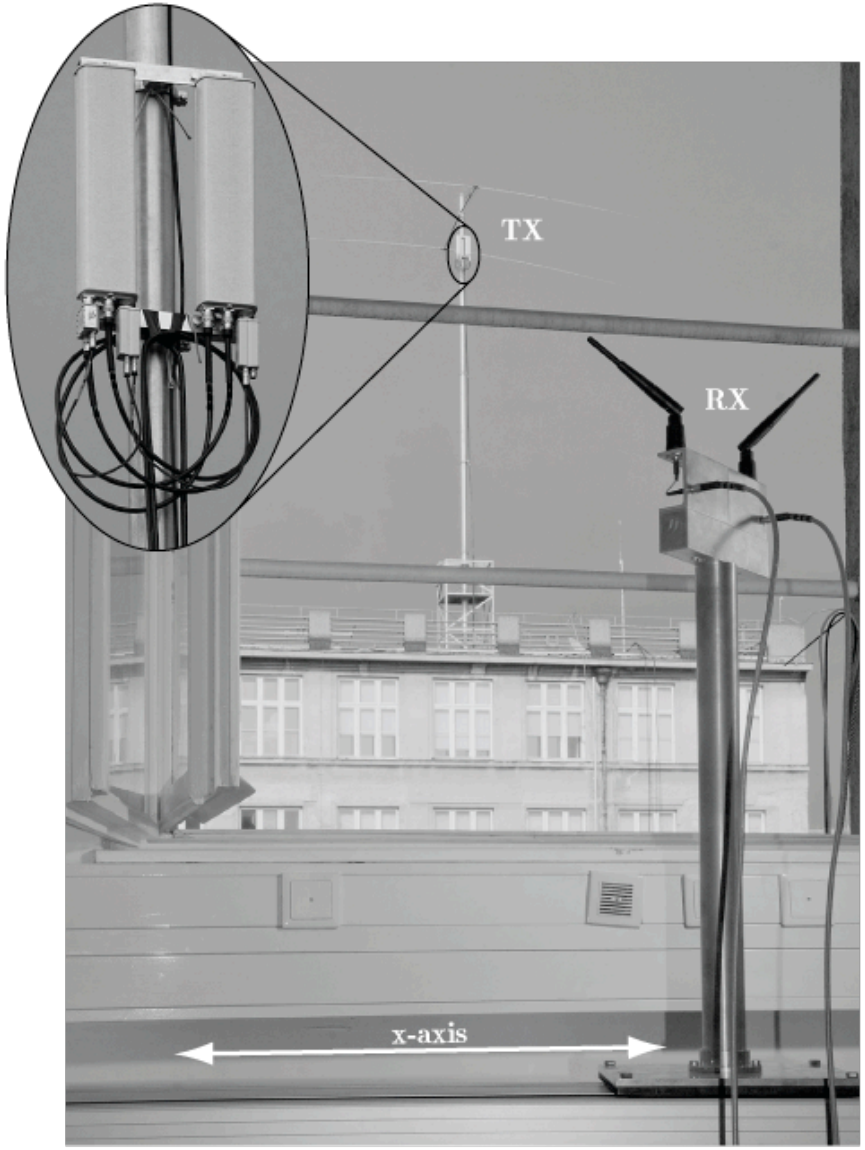
# OFDM Modulation and Demodulation



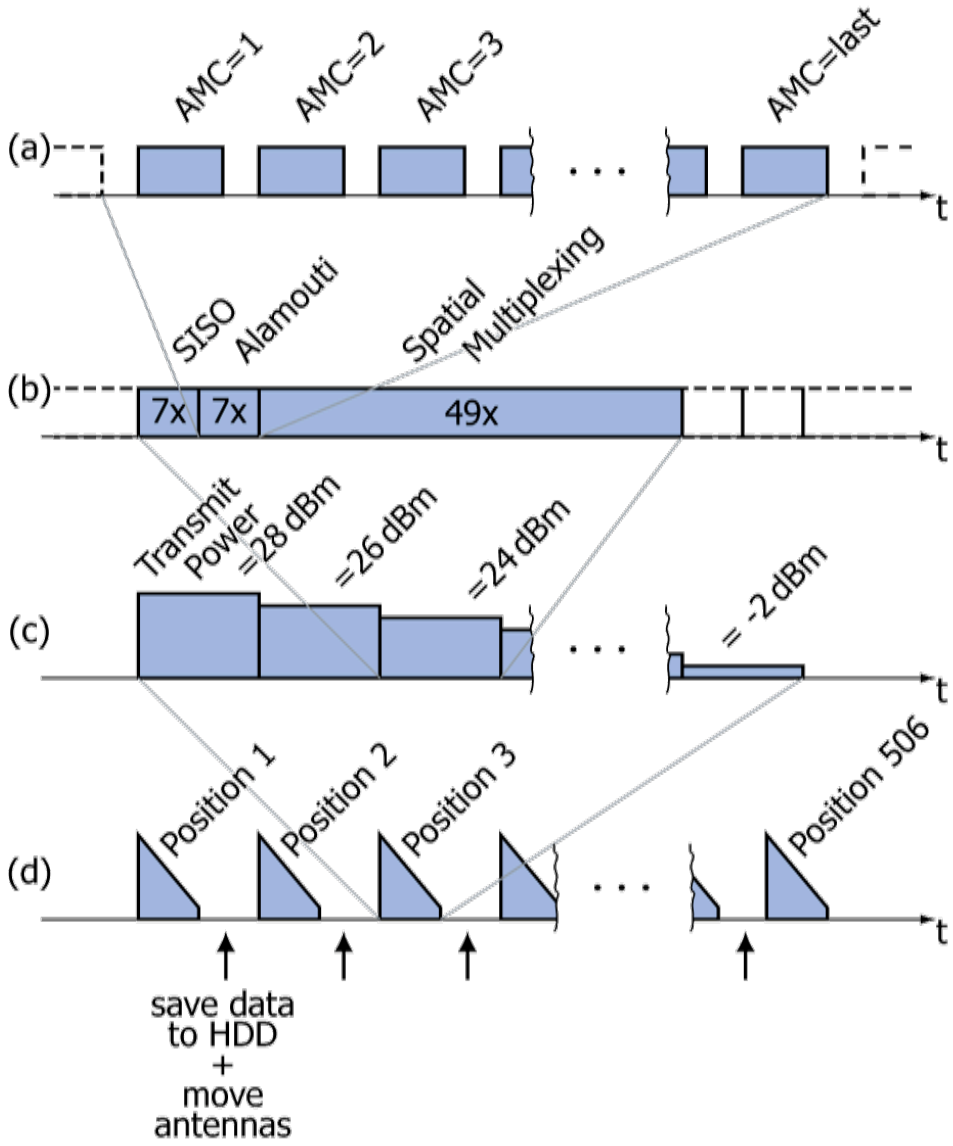
# Preliminary Measurement Setup [W2]

- 3 scenarios
  1. NLOS, outdoor-to-indoor
  2. NLOS, outdoor-to-outdoor
  3. LOS, outdoor-to-indoor
- Parameters
  - 5 MHz channel bandwidth
  - Cyclic prefix 1/4
  - 192 carrier OFDM
  - Rx antenna distance 1.2λ
  - Tx antenna distance: 2.75λ
  - Tx antenna height: 16m

Measurement distance: 50-100m

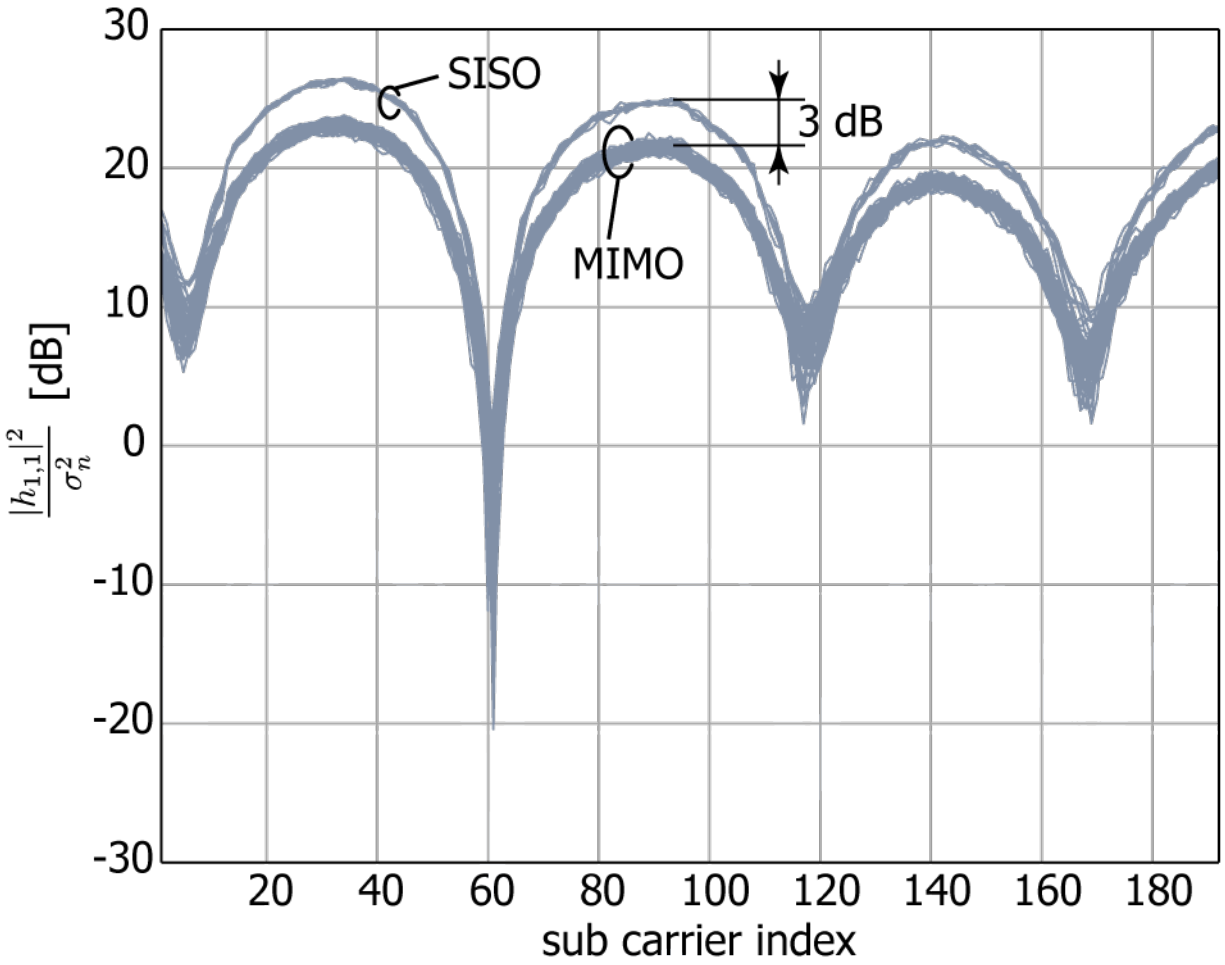


# Block Transmission [W2]



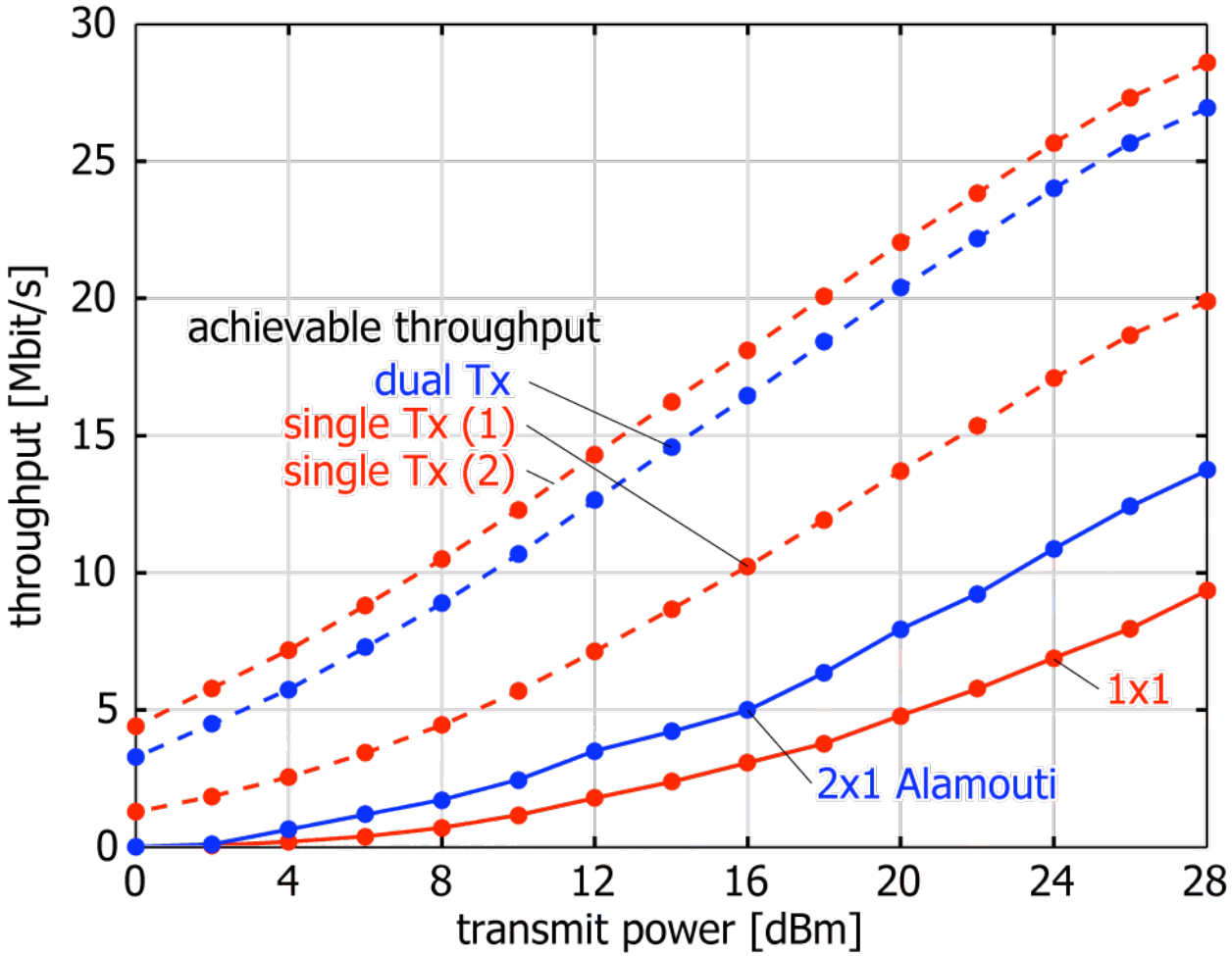

1. SIMO, 7 AMC schemes, 3 bit feedback
2. MIMO with Alamouti, 7 AMC schemes, 3 bit feedback
3. MIMO with spatial multiplexing, **same** coding scheme on both antennas, 3 bit feedback
4. MIMO with spatial multiplexing, **individual** coding schemes on both antennas, 6 bit feedback

# Measured Channel Coefficients [W2]

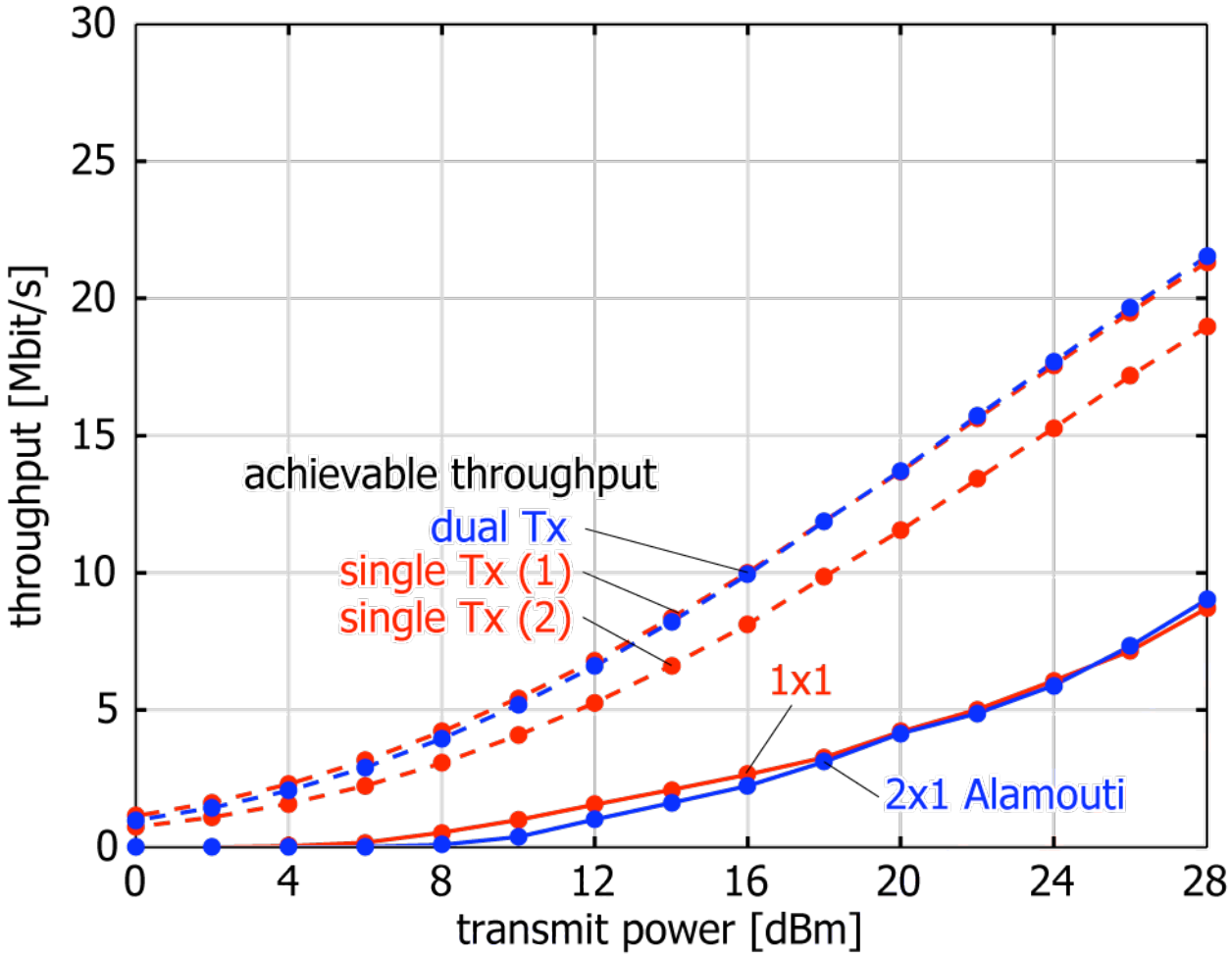



Duration of measurements: ~200ms

# One Receive Antenna: NLOS outdoor-to-outdoor [W2]



# One Receive Antenna: NLOS outdoor-to-indoor [W2]

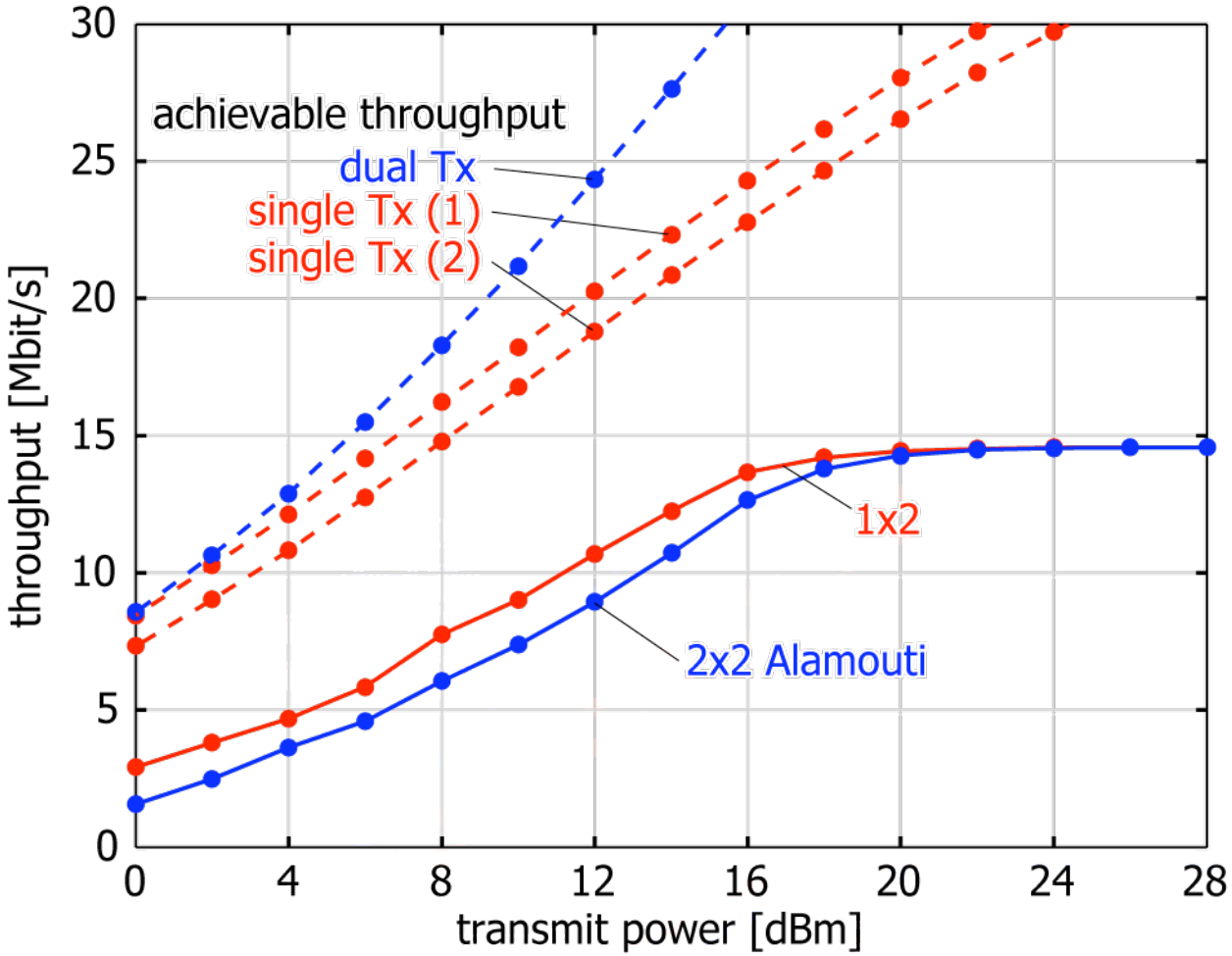


# One Receive Antenna: Conclusions [W2]

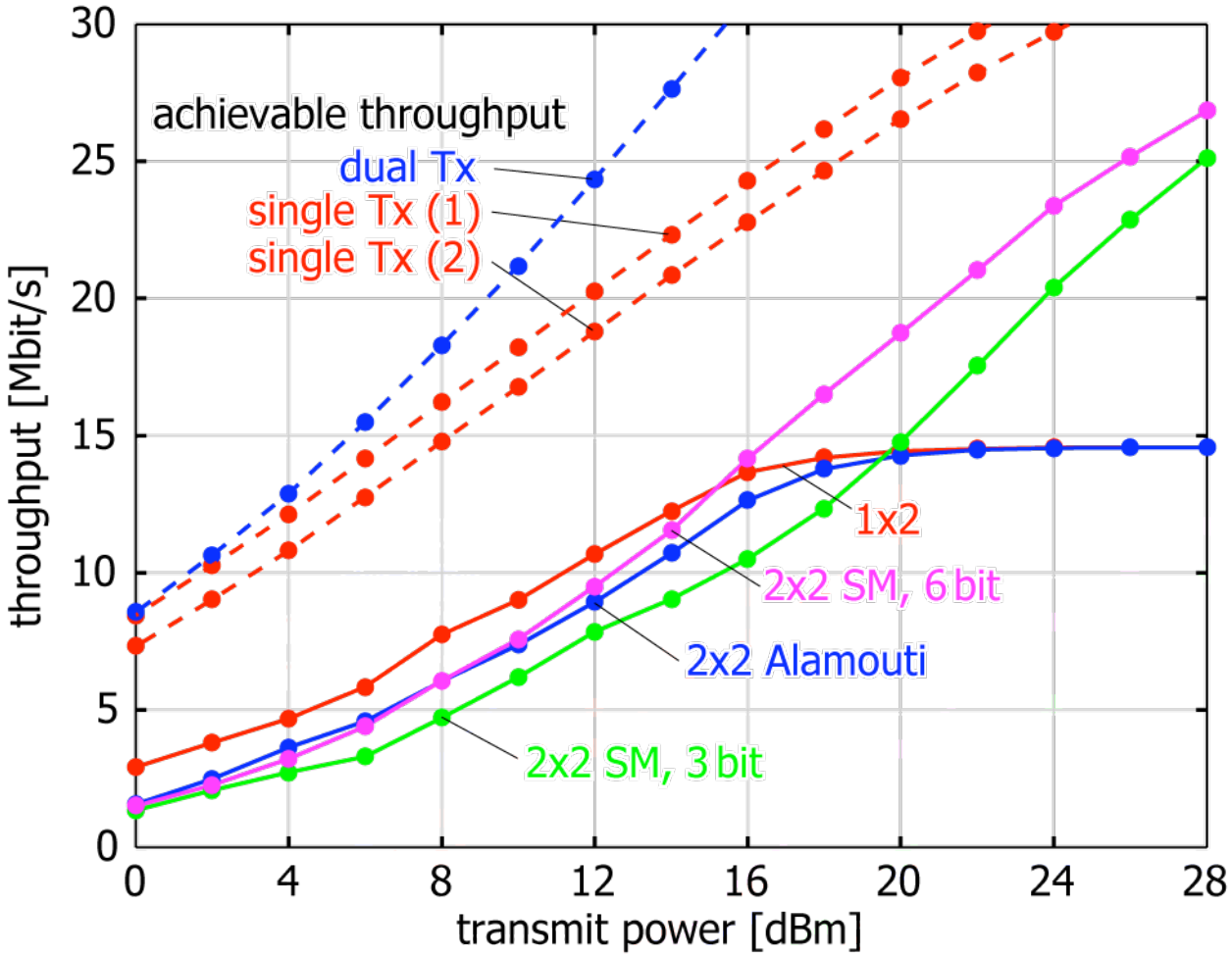
- The measured scenarios behave asymmetric with respect to the transmit antenna
- If channel is known at the transmitter, antenna selection can improve the performance
- Alamouti looses (slightly) compared to single antenna transmission
  - more sensitive channel estimation errors
  - 3dB less power for training
  - Asymmetric scenario

- Huge gap of >10 dB between measured and achievable throughput!

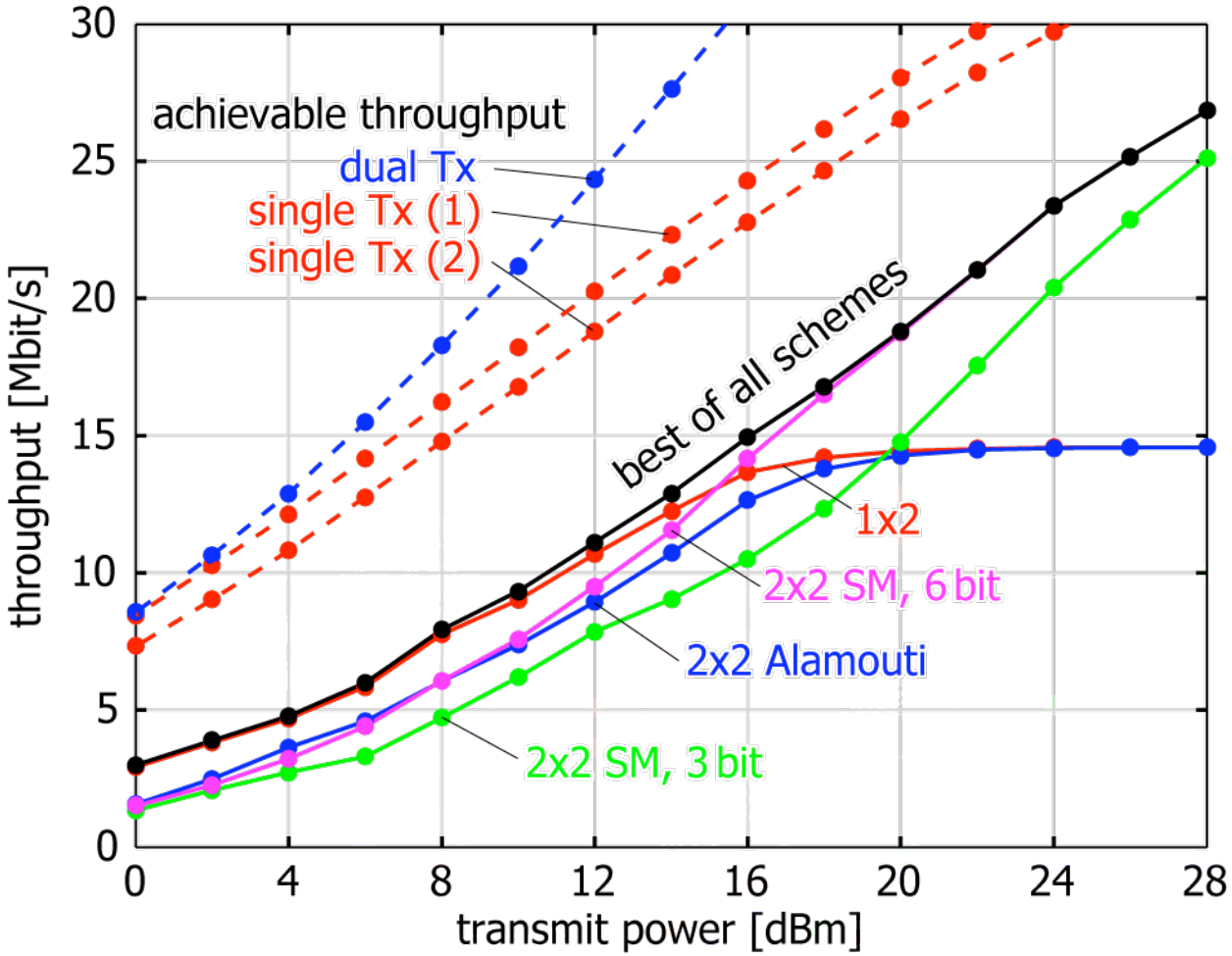
# Two Receive Antennas MRC: LOS outdoor-to-indoor [W2]



# Two Receive Antennas: LOS outdoor-to-indoor [W2]



# Two Receive Antennas: LOS outdoor-to-indoor [W2]

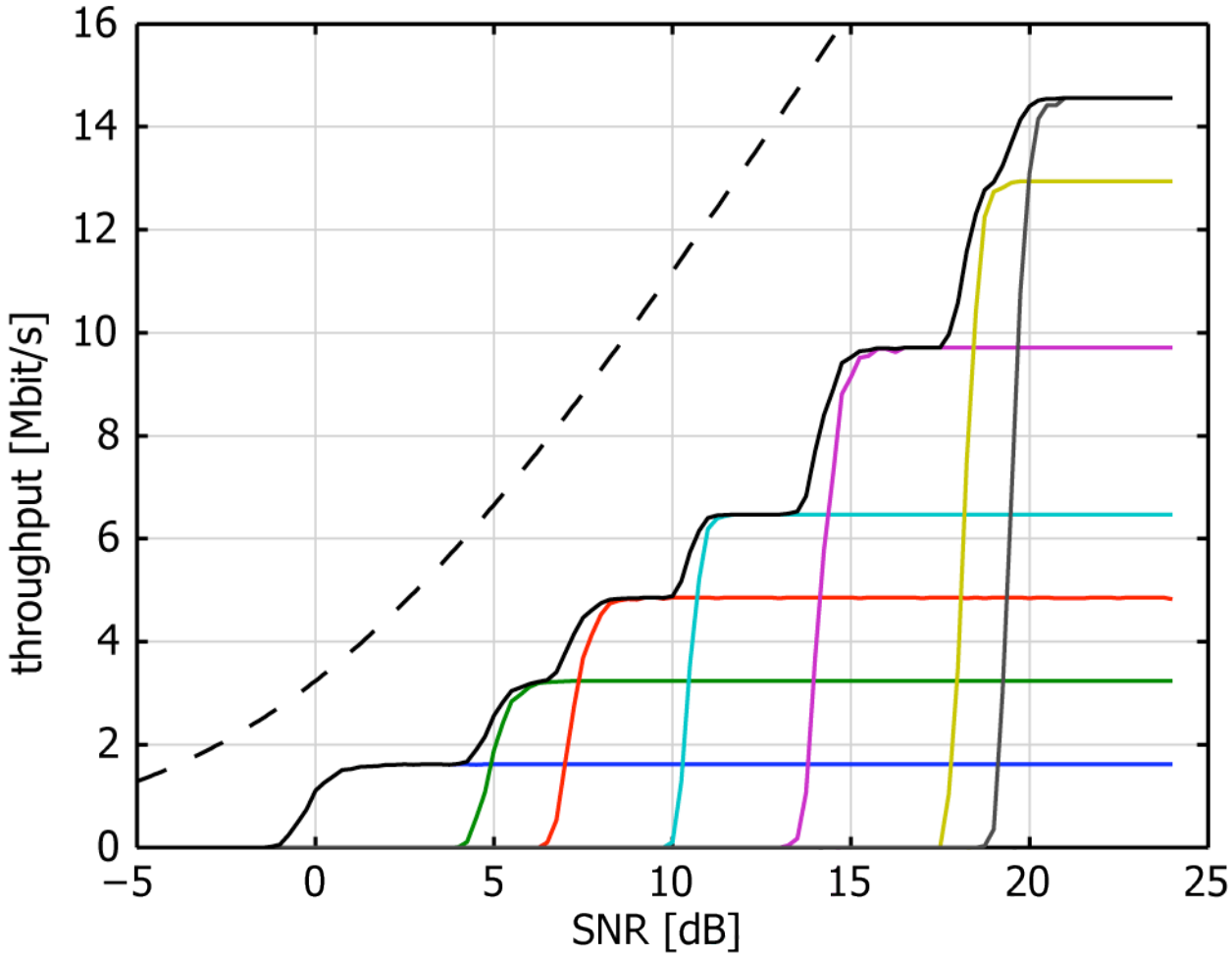


# Two Receive Antennas: Conclusions [W2]

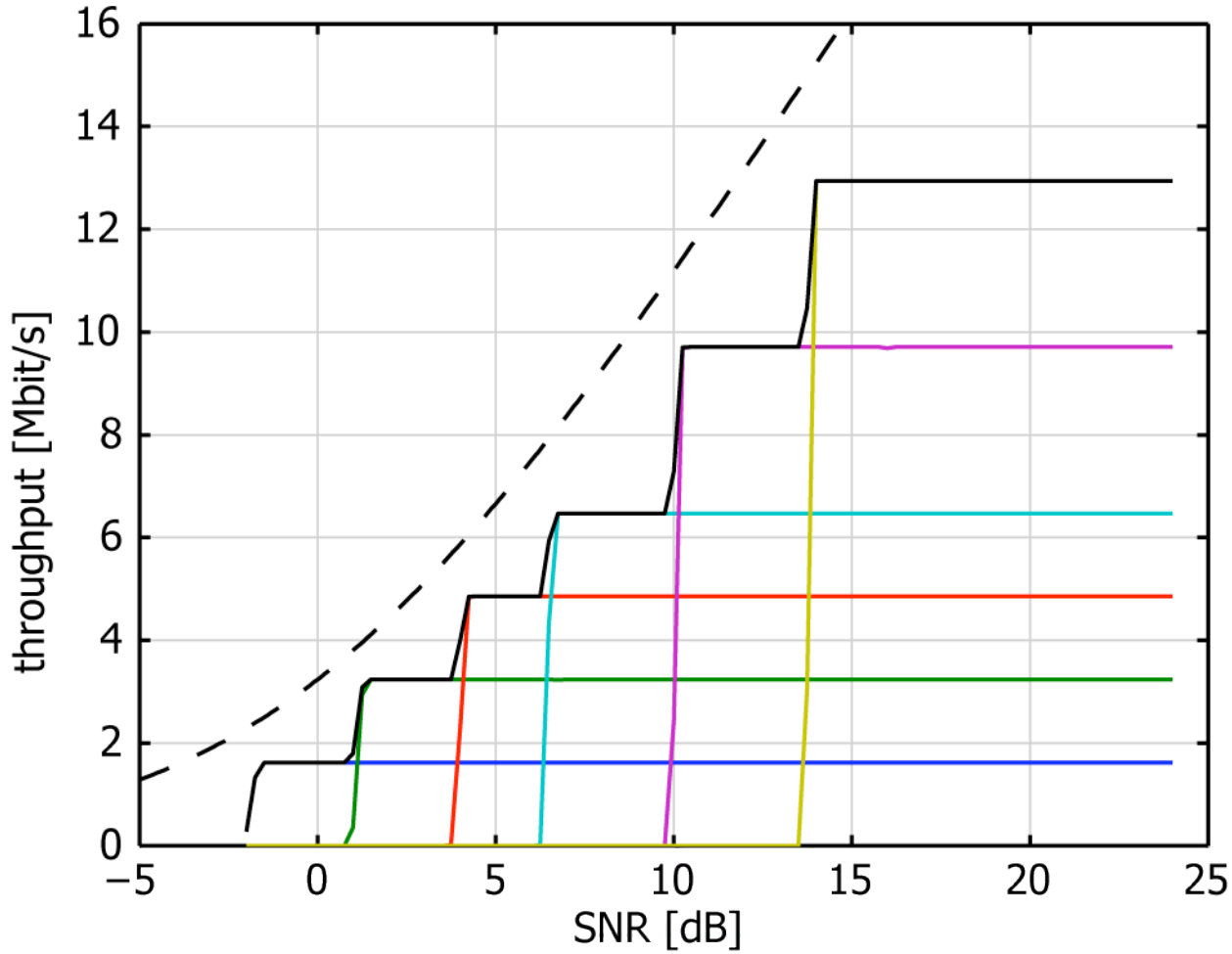
- Spatial multiplexing with 6 bit feedback outperforms spatial multiplexing with 3 bit feedback
  - The 6 bit feedback allows to exploit the asymmetric channels
- Alamouti is better than spatial multiplexing with 3 bit feedback due to transmit diversity
- Still, a huge gap of >10 dB between measured and achievable throughput is observed!

- Enhancements
  - Better channel coding
    - e.g. Low Density Parity Check (LDPC) codes
  - Enhanced channel estimation techniques
    - e.g. LMMSE channel estimation to exploit correlation between subcarriers

# AWGN Performance of the Reed Solomon-Conv.Coder



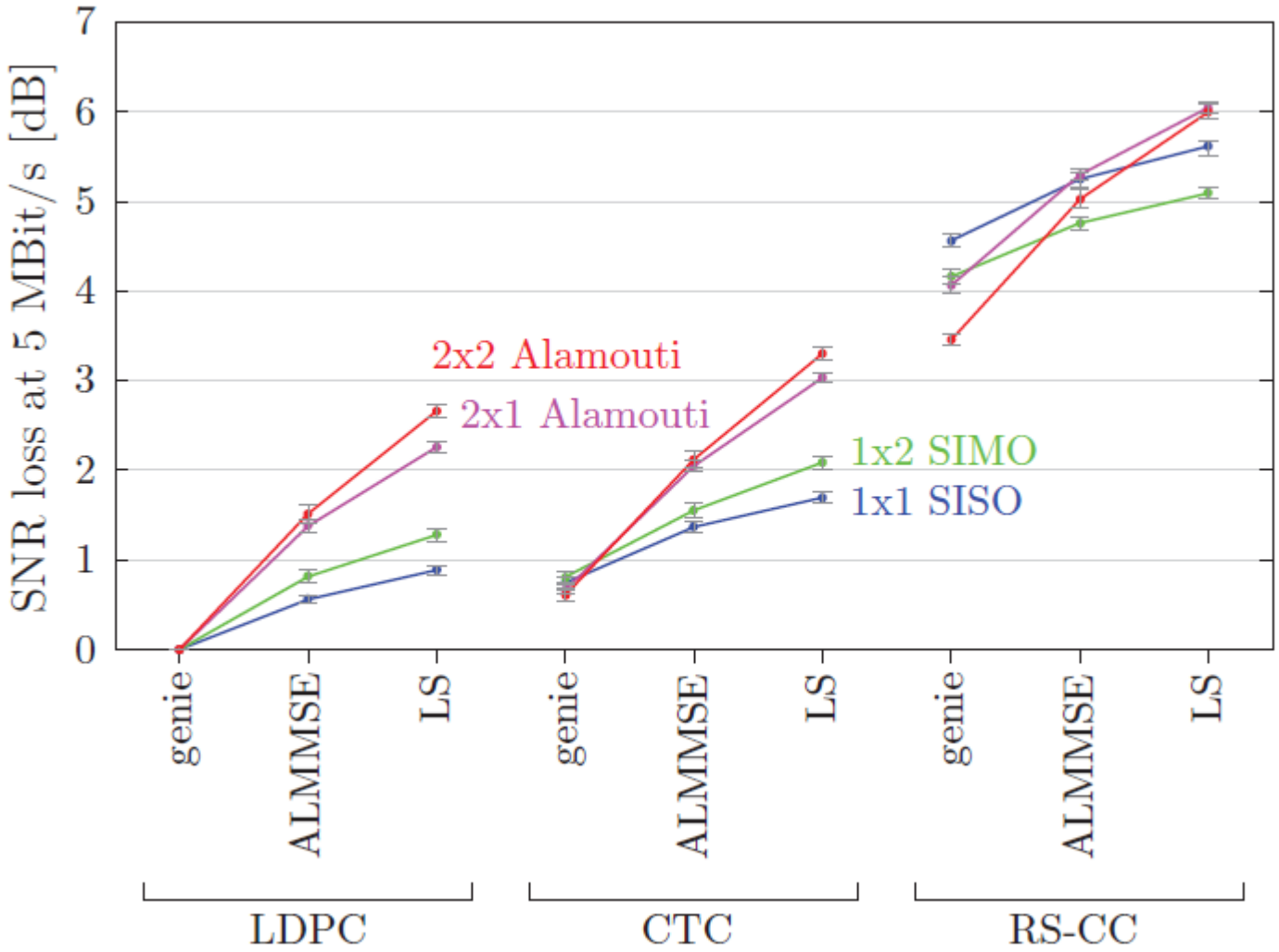
# AWGN Performance of LDPC codes



# SNR Gain of Improved Channel Estimators over the LS Estimator [W1]

| Scenario 1 | LMMSE | genie-driven |
|---|---|---|
| 1x1 SISO | 0.6 dB | 1.2 dB |
| 2x1 Alamouti | 1.8 dB | 2.9 dB |
| 1x2 SIMO | 0.5 dB | 1.2 dB |
| 2x2 Alamouti | 1.9 dB | 3.2 dB |
| 2x2 Spatial Multiplexing (3 bit) | 1.4 dB | 2.4 dB |
| 2x2 Spatial Multiplexing (6 bit) | 1.1 dB | 2.2 dB |

# Losses in WiMAX



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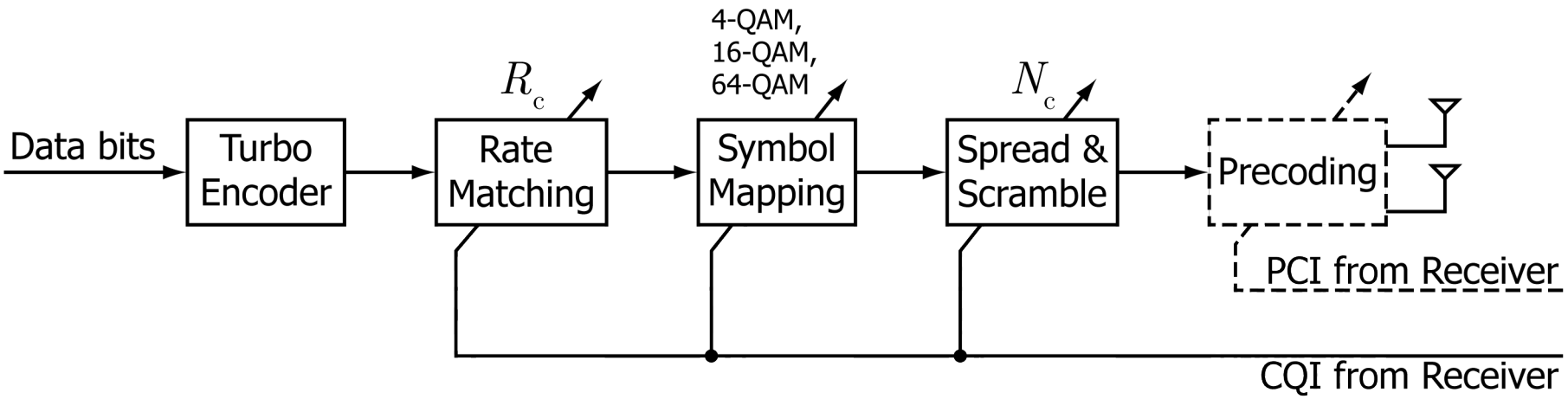
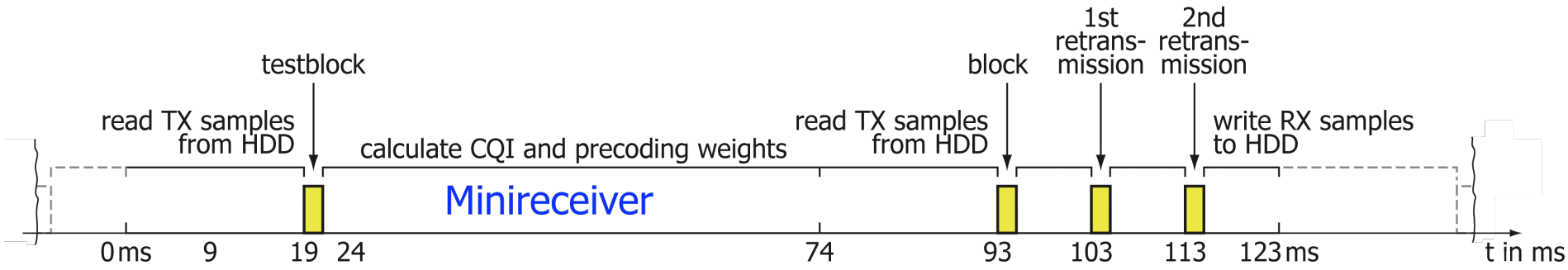
# HSDPA Overview




- Channel adaptation is performed by means of
  - a Channel Quality Indicator (CQI) and
  - a Precoding Control Indicator (PCI) when two transmit antennas are available

# Transmission Timing [H4]




- Large number of possible transmit blocks require channel evaluation at the receiver
- Minireceiver estimates channel and noise and calculates the CQI and PCI

# SINR Estimation in Minireceiver [H5]

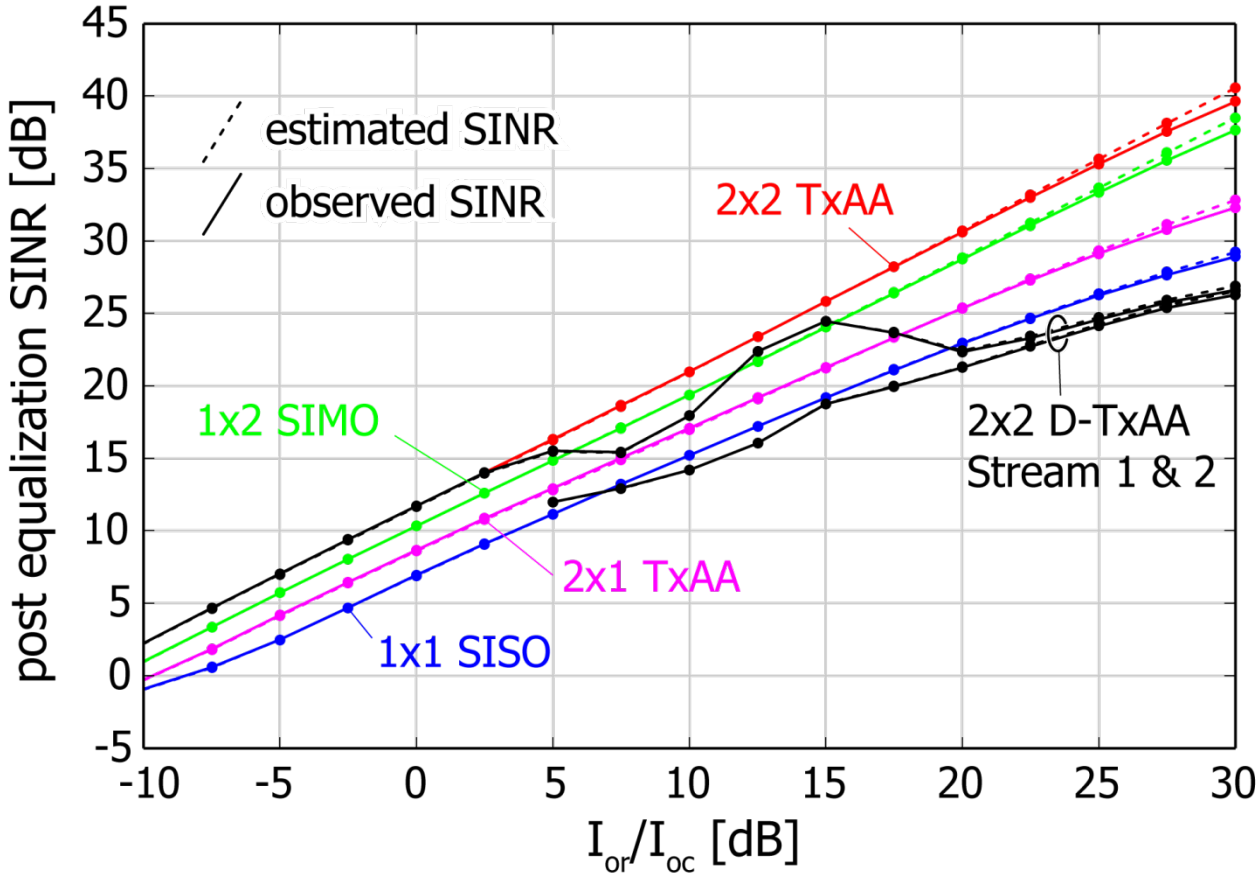
$$\mathrm{SINR}_{\mathrm{est}} = \frac{P_s}{\sigma_{n'}^2 + P_{\mathrm{ISI}} + P_{\mathrm{INT}}}$$

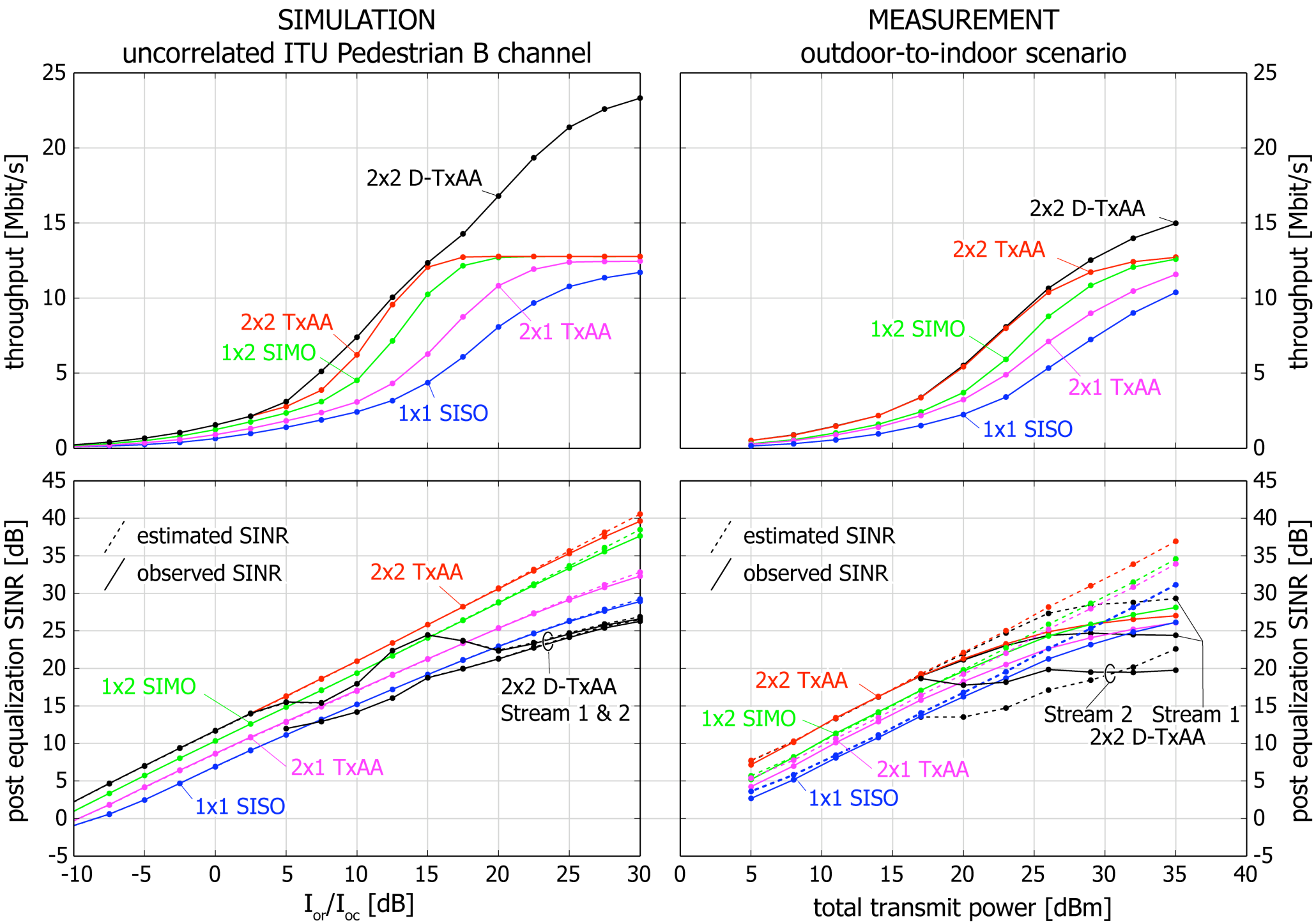
The post equalization SINR is given by

- the signal power $P_s$
- the noise at the output of the equalizer $\sigma_{n'}^2$
- the remaining inter-symbol interference $P_{\mathrm{ISI}}$
- the interference caused by spatially multiplexed streams sharing the same scrambling and spreading codes $P_{\mathrm{INT}}$

SINR is calculated for all possible precoding vectors and mapped to the supported CQI values. The precoding vector maximizing the transport block size is selected.

# Verification of the SINR Estimation in the Simulation [H5]




SIMULATION
uncorrelated ITU Pedestrian B channel
MEASUREMENT
outdoor-to-indoor scenario
throughput [Mbit/s]
post equalization SINR [dB]
2x2 D-TxAA
2x2 TxAA
1x2 SIMO
2x1 TxAA
1x1 SISO
estimated SINR
observed SINR
2x2 D-TxAA
Stream 1 & 2
Stream 2
Stream 1
$I_{or}/I_{oc}$ [dB]
total transmit power [dBm]

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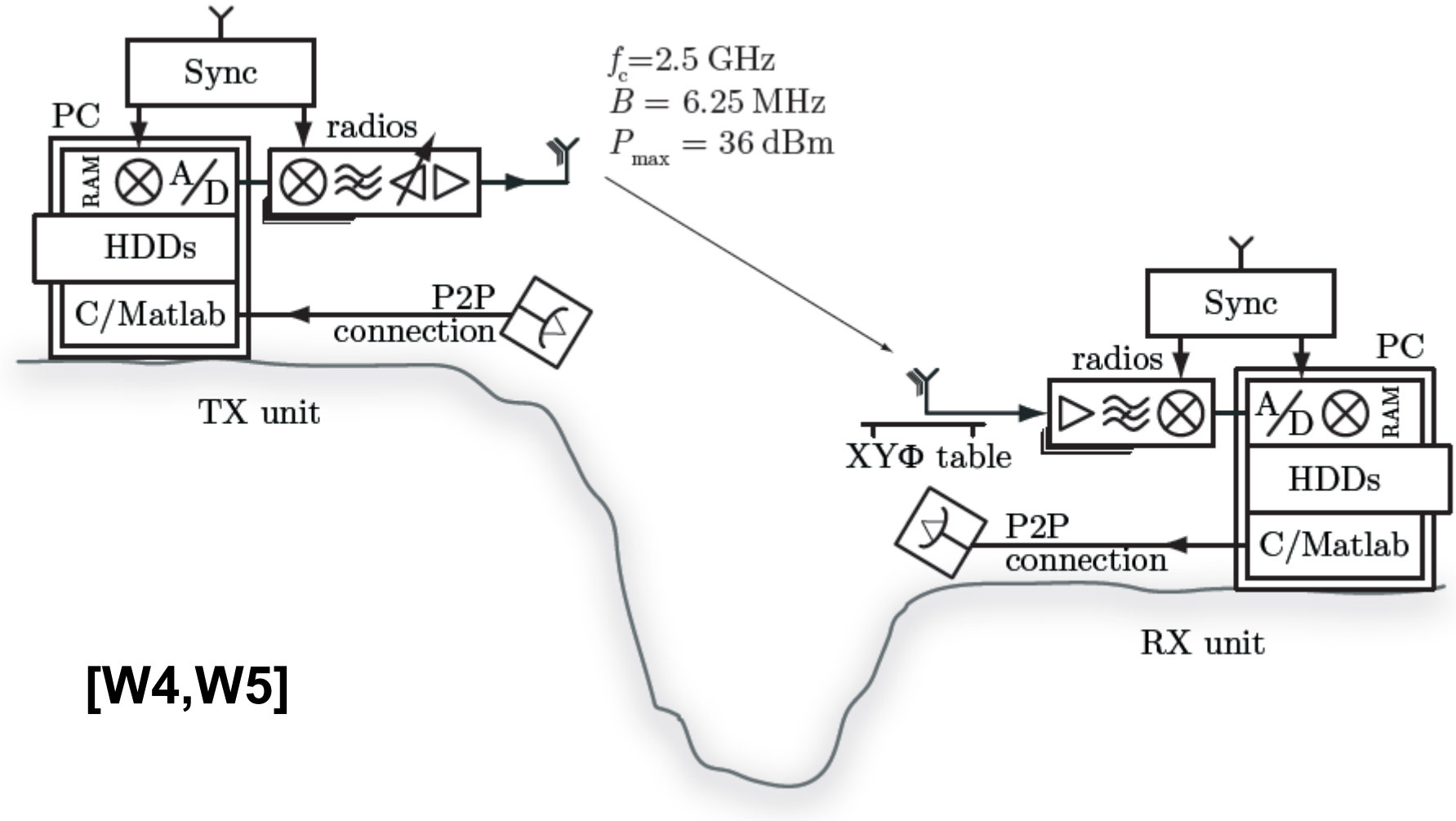
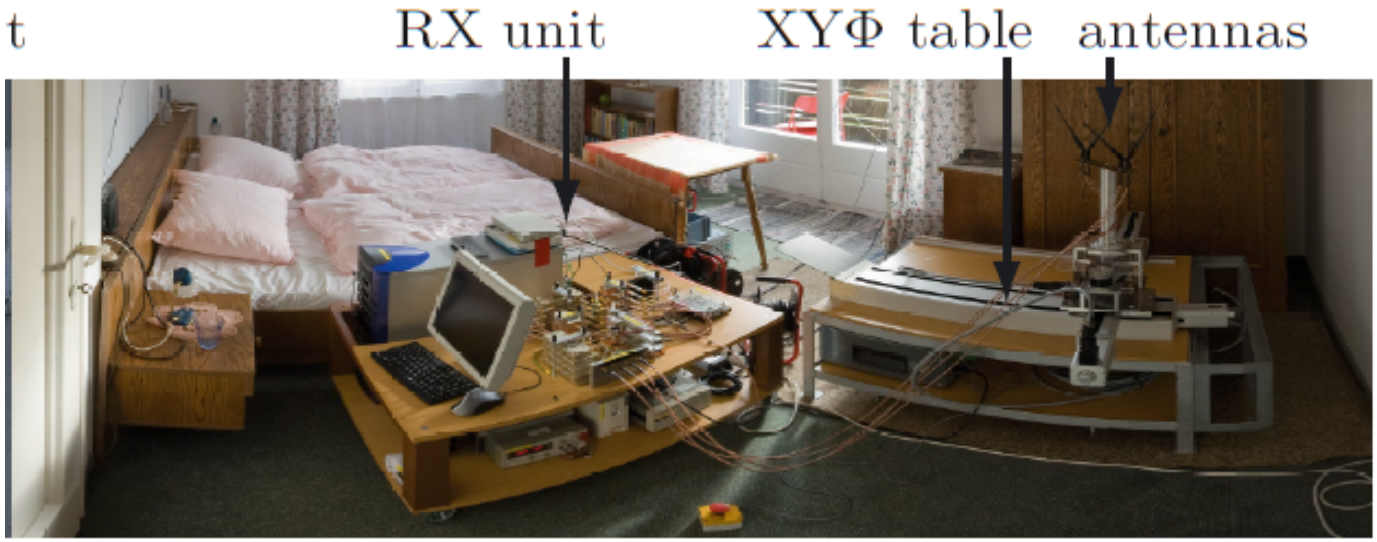
# Two Measurement Campaigns: Alpine and Urban




**[W4,W5]**

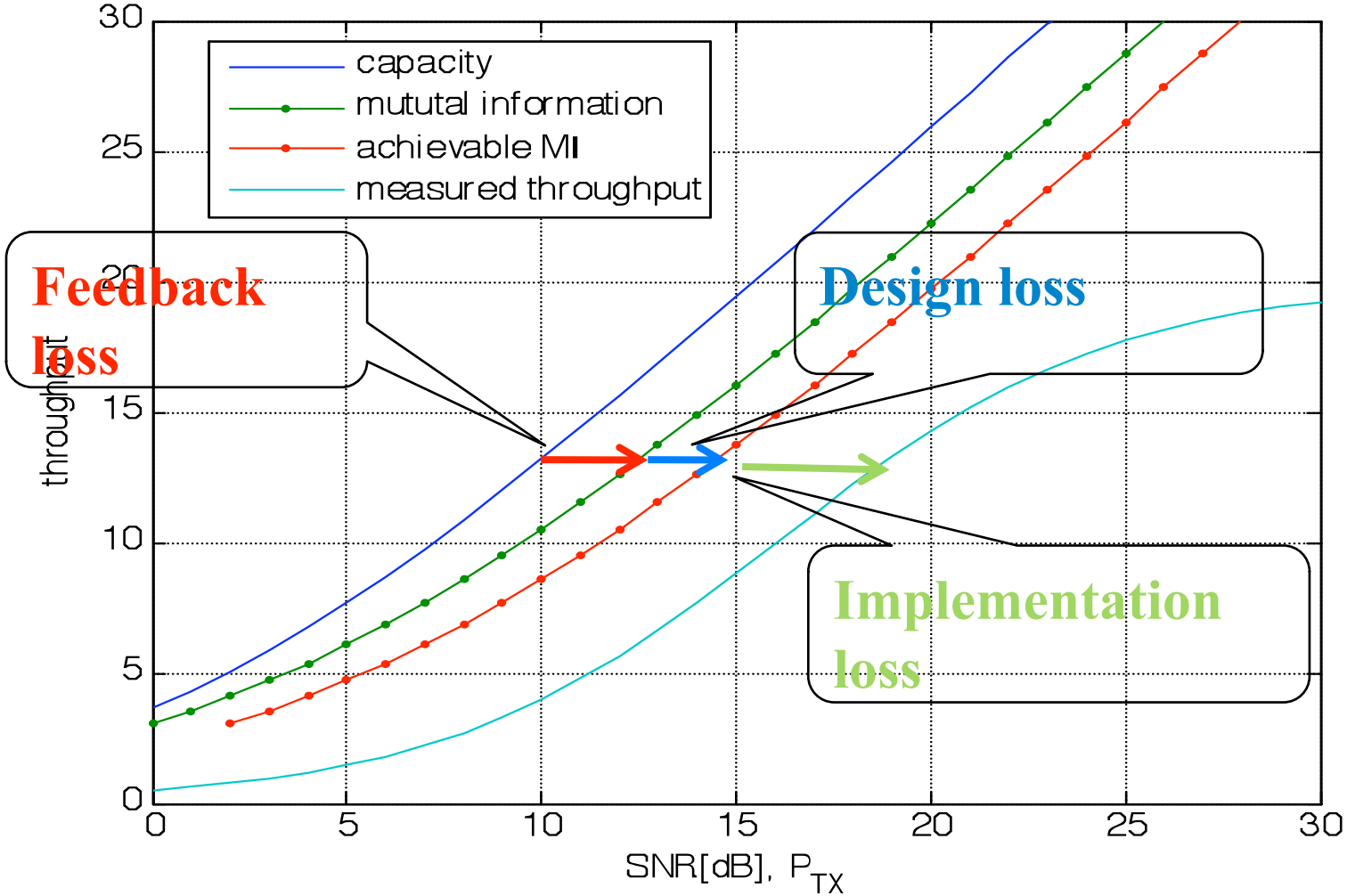
# Two Measurement Campaigns: Alpine and Urban

# Two Measurement Campaigns: Alpine and Urban

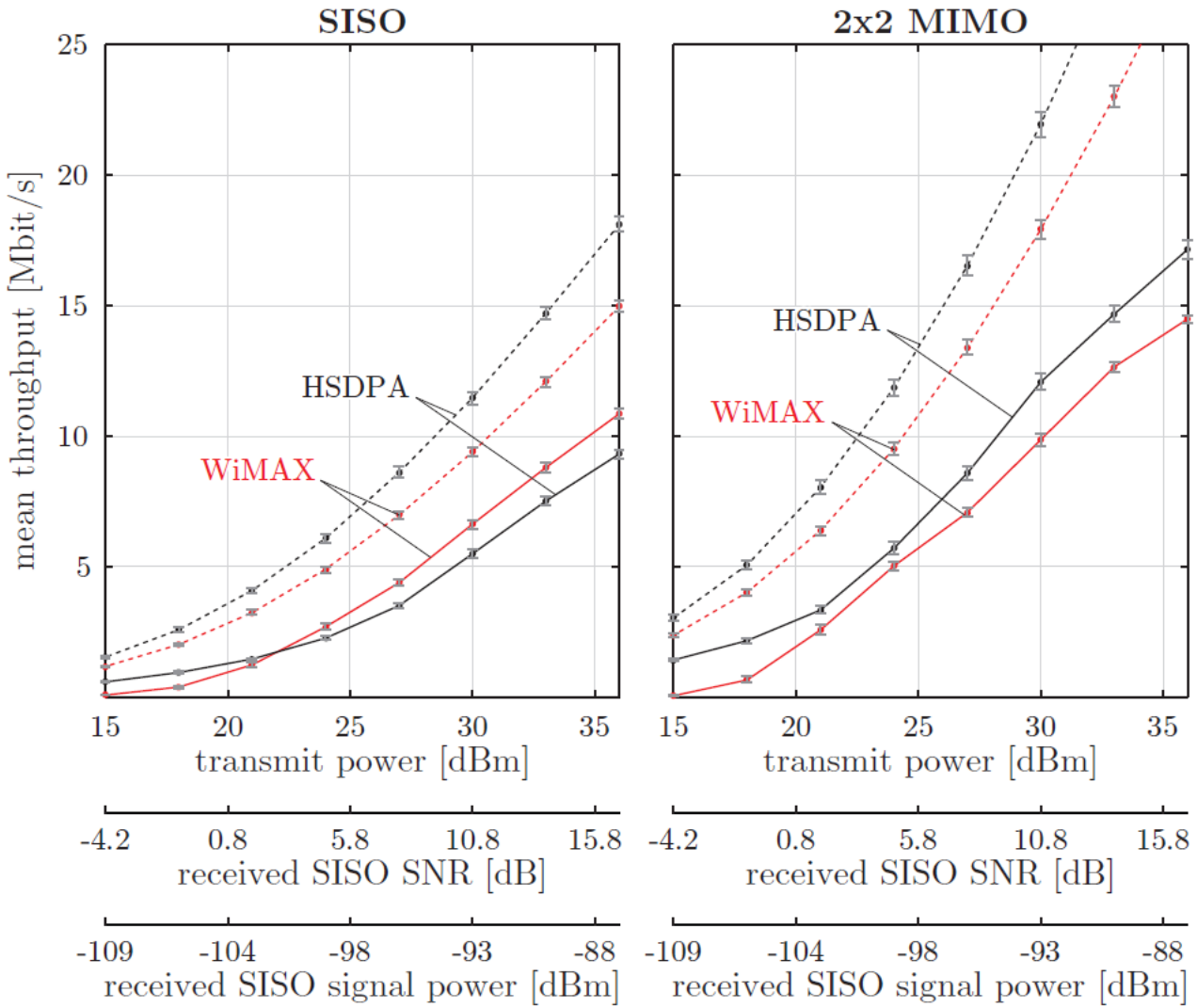

**[C1,C2,C3,C4]**

# Performance Comparisons



# HSDPA vs WiMAX in Alpine Environment

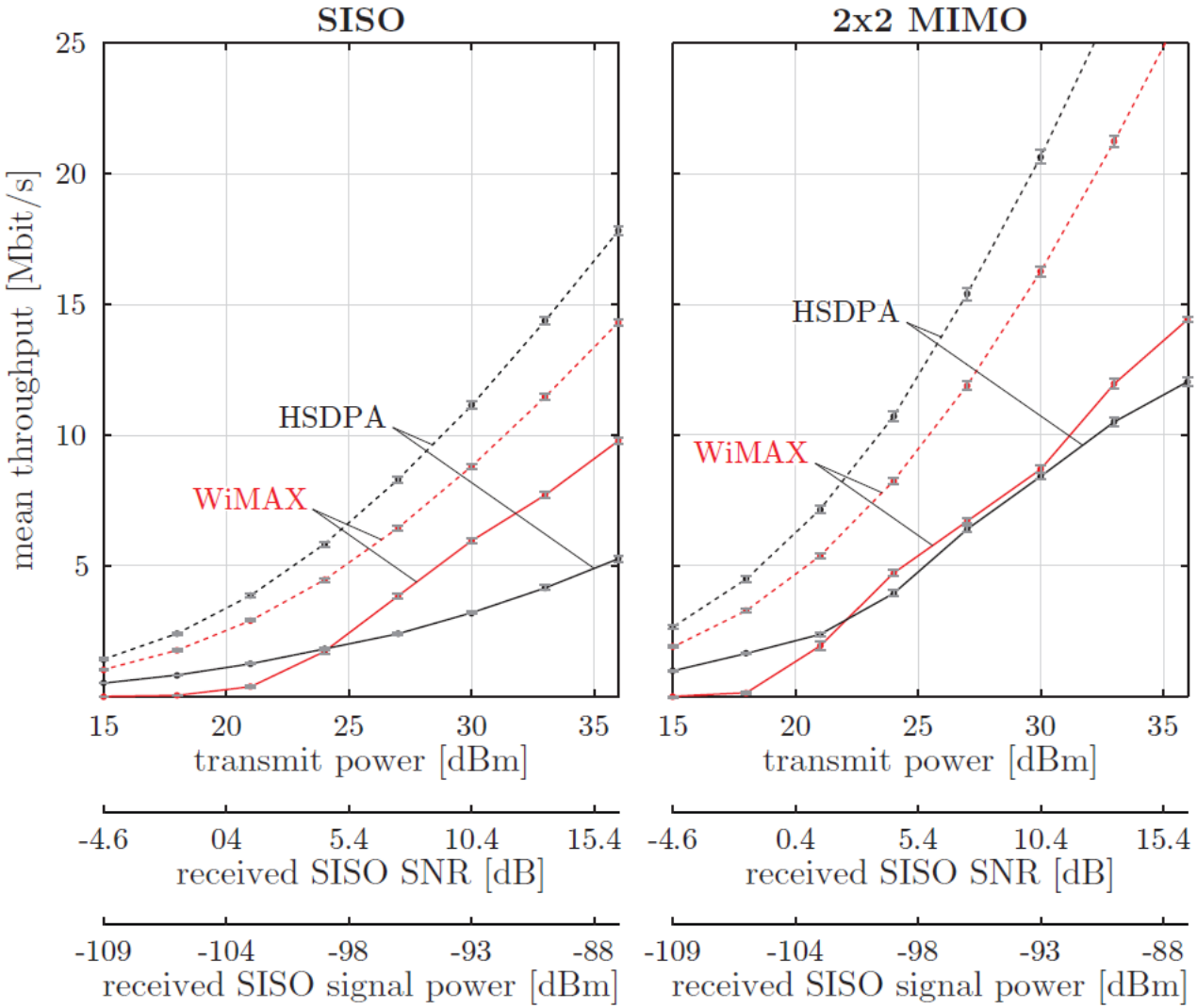
## Achievable Throughput vs. Achieved Throughput




Implementation loss

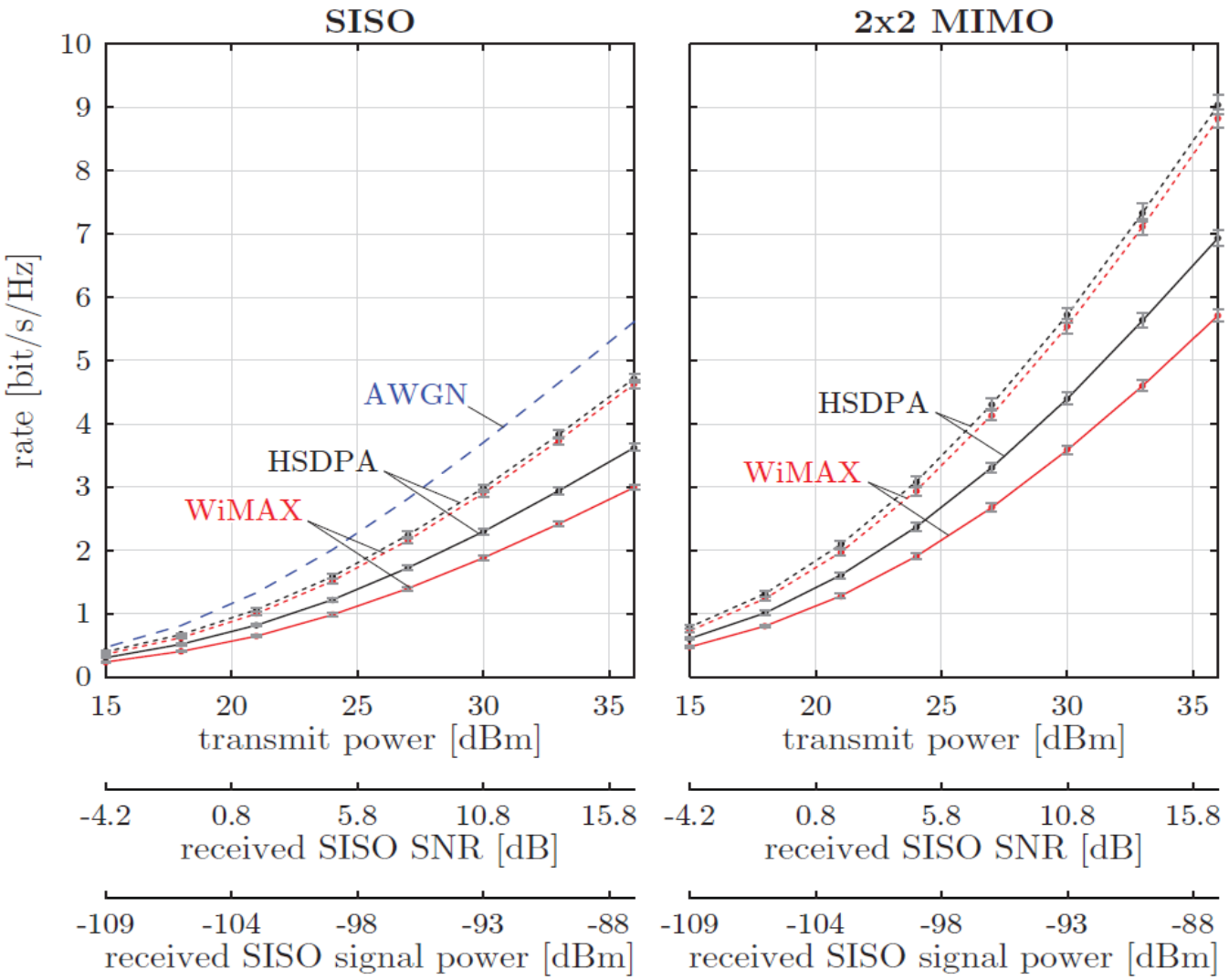
# HSDPA vs WiMAX in Urban Environment

## Achievable Throughput vs. Achieved Throughput




Implementation loss

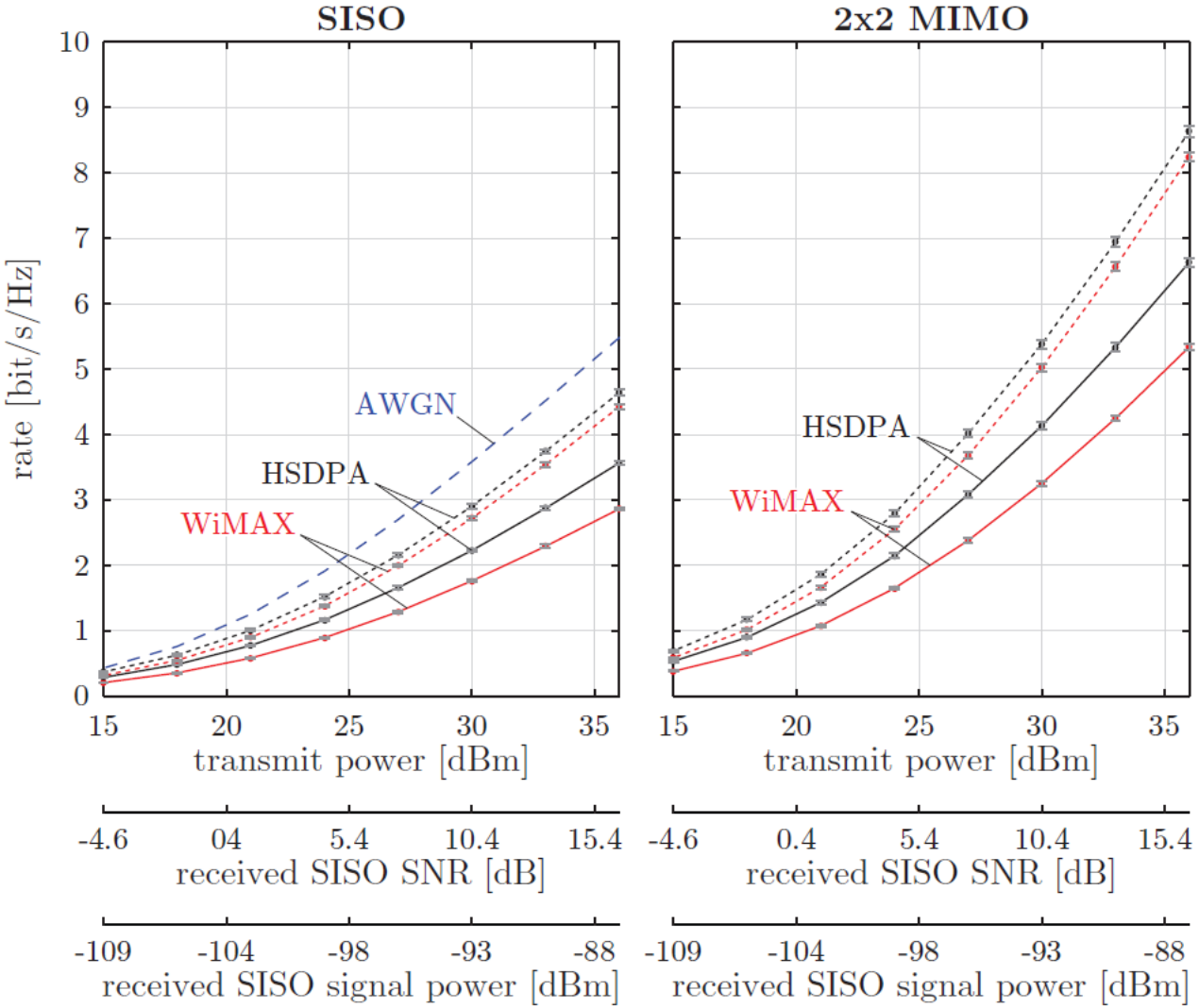
# HSDPA vs WiMAX in Alpine Environment
## Mutual Information vs Achievable Throughput




**Design loss**

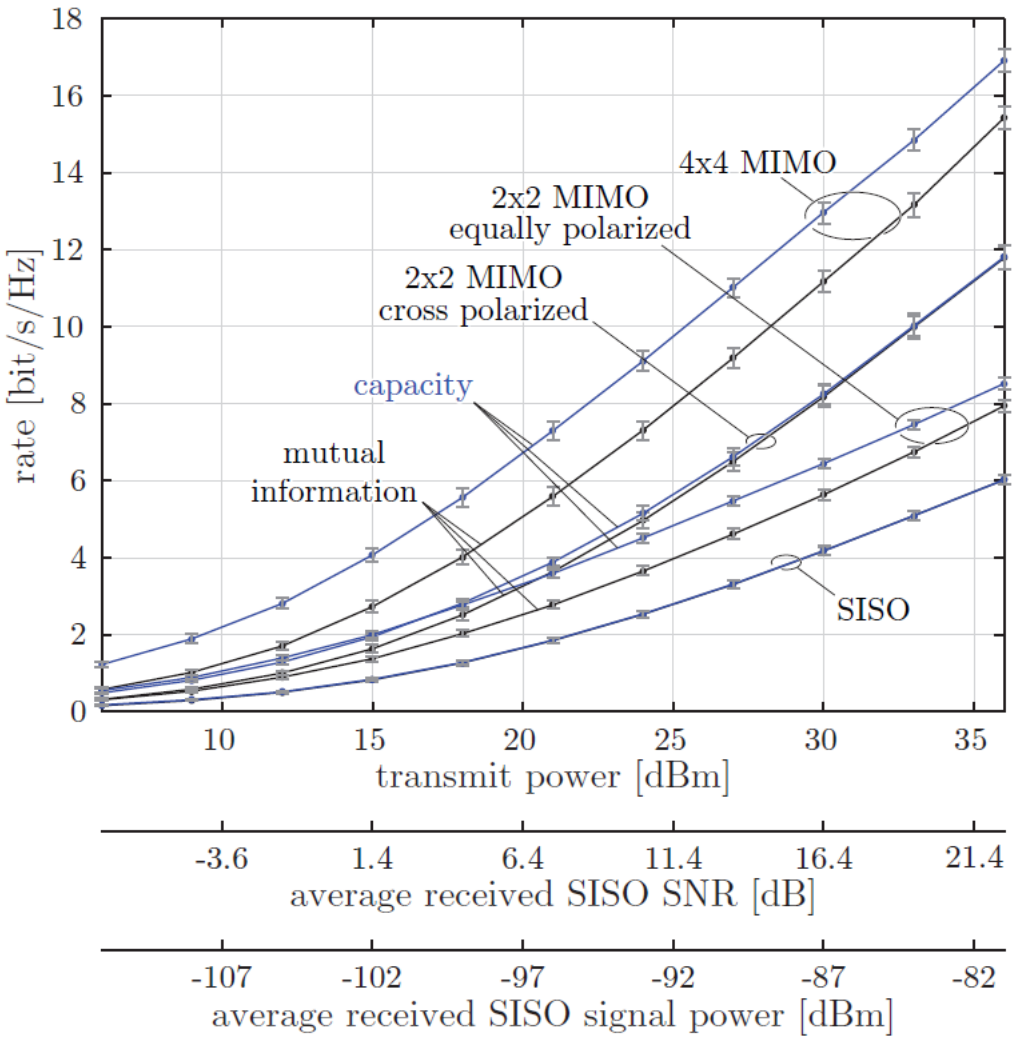
# HSDPA vs WiMAX in Urban Environment

## Mutual Information vs Achievable Throughput



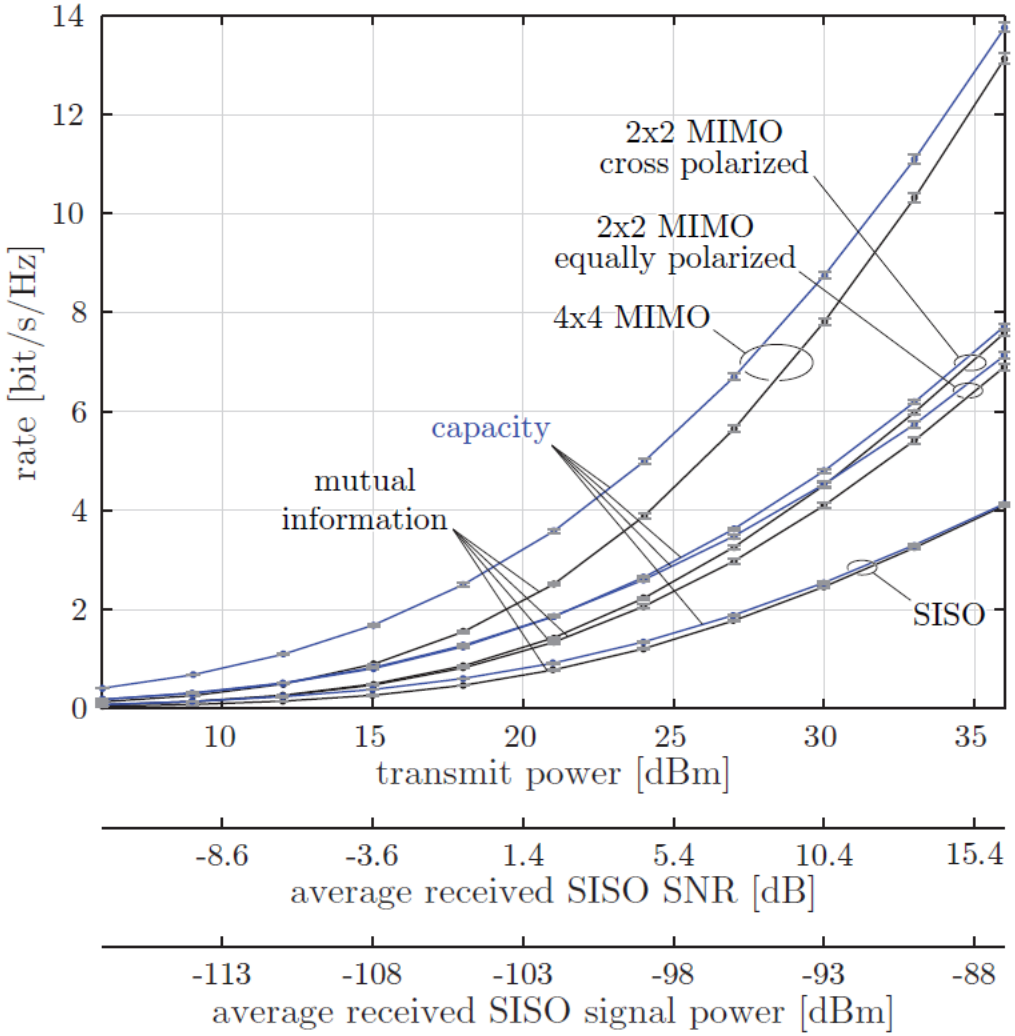

**Design loss**

# HSDPA vs WiMAX in Alpine Environment
## Capacity vs Mutual Information




**Feedback loss**

# HSDPA vs WiMAX in Urban Environment
## Capacity vs Mutual Information




**Feedback loss**

# Conclusion

- WiMAX and HSDPA are ~10dB off from the Shannon Bound!

- Channel estimation loss
  - 2-3dB channel estimator
  - 6-9dB in HSDPA due to self-interference
- Coding loss
  - 5dB convolutional codes (WiMAX)
  - 2-3dB Turbo
  - 1-2dB LDPC
- CQI (PCI) indicators need to be selected optimally
  - 1-2dB loss depending on scenario

# Thank you for your attention.

http://www.nt.tuwien.ac.at/

# Testbed References


[T1] Sebastian Caban, Christian Mehlführer, Robert Langwieser, Arpad L. Scholtz, Markus Rupp, "**Vienna MIMO Testbed**," in *EURASIP JASP Special Issue on Implementation Aspects and Testbeds for MIMO Systems,* Vol. 2006, Article ID 54868 (2006), http://publik.tuwien.ac.at/files/pub-et_10929.pdf.

[T2] Markus Rupp, Christian Mehlführer, Sebastian Caban, Robert Langwieser, Lukas W. Mayer, Arpad L. Scholtz, "**Testbeds and Rapid Prototyping in Wireless System Design**," in *EURASIP Newsletter,* 17 (2006), pp. 32-50, http://publik.tuwien.ac.at/files/pub-et_11232.pdf.

[T3] Thomas Kaiser, Andreas Wilzeck, Martin Berentsen, Markus Rupp, "**Prototyping for MIMO Systems - an Overview,"** in Proc. 12th European Signal Processing Conference (EUSIPCO 2004), Vienna, Austria, pp. 681-688, Sept. 2004, http://publik.tuwien.ac.at/files/pub-et_8809.pdf.

[T4] Markus Rupp, Andreas Burg, Eric Beck, "**Rapid prototyping for wireless designs: the five-ones approach,"** in Signal Processing, vol. 83, Issue 7, pp. 1427-1444, July 2003, http://publik.tuwien.ac.at/files/pub-et_7159.pdf.

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[H2] Martin Wrulich, Christian Mehlführer, Markus Rupp, "**Interference Aware MMSE Equalization for MIMO TxAA**," in Proc. International Symposium on Communications, Control, and Signal Processing 2008 (ISCCSP 2008) , pp. 1585-1589, St. Julians, Malta, Mar. 2008, http://publik.tuwien.ac.at/files/pub-et_13657.pdf.

[H3] Christian Mehlführer, Martin Wrulich, Markus Rupp, "**Intra-cell Interference Aware Equalization for TxAA HSDPA**," in Proc. IEEE International Symposium on Wireless Pervasive Computing (ISWPC 2008), pp. 406-409, Santorini Greece, http://publik.tuwien.ac.at/files/pub-et_13749.pdf.

[H4] Christian Mehlführer, Sebastian Caban, Markus Rupp, "**Measurement based evaluation of low complexity receivers for D-TxAA HSDPA**," in Proc. 16th European Signal Processing Conference (EUSIPCO 2008), Lausanne, Aug. 2008. http://publik.tuwien.ac.at/files/PubDat_166132.pdf

[H5] Christian Mehlführer, Sebastian Caban, Martin Wrulich, and Markus Rupp, "**Joint Throughput Optimized CQI and Precoding Weight Calculation for MIMO HSDPA**," submitted to 42nd Asilomar Conference on Signals, Systems and Computers, 2008, Pacific Grove, CA, USA, Oct. 2008. http://publik.tuwien.ac.at/files/PubDat_167015.pdf

[H6] Christian Mehlführer, Markus Rupp, "**Novel Tap-wise LMMSE channel estimation for MIMO W-CDMA**," 51st Annual IEEE Globecom Conference 2008, New Orleans, LA, USA, Nov. 2008. http://publik.tuwien.ac.at/files/PubDat_169129.pdf

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[W2] Christian Mehlführer, Sebastian Caban, Markus Rupp, "**Experimental Evaluation of Adaptive Modulation and Coding in MIMO WiMAX with Limited Feedback**," in *EURASIP JASP Special Issue on MIMO Transmission with Limited Feedback,* Vol. 2008, Article ID 837102 (2008), http://publik.tuwien.ac.at/files/pub-et_13762.pdf

[W3] Dagmar Bosanska, Christian Mehlführer, Markus Rupp, "**Channel Adaptive OFDM Systems with Packet Error Rate Adaptation**," Proc. of Workshop on on Smart Antennas (WSA09), Berlin, Feb. 2009. http://publik.tuwien.ac.at/files/PubDat_175538.pdf

[W4] Qi Wang, Christian Mehlführer, Markus Rupp, "**SNR Optimized Residual Frequency Offset Compensation for WiMAX with Througput Evaluation**," EUSIPCO conference, Glasgow, UK, August 2009. http://publik.tuwien.ac.at/files/PubDat_176678.pdf

[W5] Qi Wang, Sebastian Caban, Christian Mehlführer, Markus Rupp, "**Measurement based Evaluation of Residual Frequency Offset Compensation in WiMAX**," ELMAR conference, Zadar, Sept. 2009.

# Comparisons


[C1] Sebastian Caban, Christian Mehlführer, Gottfried Lechner, Markus Rupp, "**Testbedding MIMO HSDPA and WiMAX**," VTC Fall, Anchorage US, Sept. 2009. http://publik.tuwien.ac.at/files/PubDat_176574.pdf

[C2] Jose A. Garcia-Naya, Christian Mehlführer, Sebastian Caban, Markus Rupp, Luis Castedo, "**Throughput-based Antenna Selection Measurements**," VTC Fall, Anchorage US, Sept. 2009. http://publik.tuwien.ac.at/files/PubDat_176573.pdf

[C3] Christian Mehlführer, Sebastian Caban, Markus Rupp, "**MIMO HSDPA Throughput Measurement Results in an Urban Scenario**," VTC Fall, Anchorage US, Sept. 2009. http://publik.tuwien.ac.at/files/PubDat_176321.pdf

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